

Traditional Medicine and Nanotechnology Integration: A Review

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Abstract

Traditional Drug practices gauge centuries and appear in colorful societies. Systems like Ayurveda, Traditional Chinese Medicine, Unani, and Siddha calculate on phrasings from sauces, minerals, and beast sources. These remedies show some remedial pledge. Yet challenges persist. Issues include poor solubility, low bioavailability, inconsistent standardization, and uneven safety. similar factors limit wider global use. Nanotechnology way in with nano formulation styles. It provides ways to address these problems. This field blends old knowledge with current wisdom. Approaches involve liposomes, polymeric nanoparticles, nano emulsions, nanogels, and solid lipid nanoparticles. substantiation suggests they ameliorate solubility, stability, and targeted delivery for factory composites. exemplifications include curcumin, quercetin, and artemisinin. Mineral medications from tradition, similar as Bhasma's, admit fresh aesthetics through ultramodern tools. Analysis reveals nanoscale patches. These structures likely explain their goods. Essence nanoparticles come from gold, tableware, and zinc. They hold implicit for crack care, fighting microbes, and boosting impunity. This overview looks at where nanotechnology meets traditional drug. It covers treatment uses, new individual tools, and hurdles in moving forward. Ancient perceptivity brace with advanced nanoscience. The result points toward integrated styles. These could yield safer, better curatives backed by data. Looking ahead, studies need strong

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checks on toxin. Clinical tests matter too. brigades from different fields should work together. Only also can nano- enhanced traditional options fit responsibly into worldwide health care.

Keywords: Nanotechnology; Traditional medicine; Herbal nano formulations; Bhasma; Nano-delivery

Introduction

Traditional medicine stands as one of the earliest and broadest systems of health care in human history. It developed over many centuries from practical observations, spiritual understandings, and local knowledge sources [1]. Diverse approaches fall under this umbrella, including Ayurveda, Traditional Chinese Medicine, Unani, Siddha, along with herbal traditions from Africa and Native American cultures. Each one draws from a complete view of health and illness. The World Health Organization reports that around 80% of people worldwide depend on these traditional or plant derived remedies for basic health care [2]. This holds especially true in less developed areas. Such widespread use points to the easy access and low cost of these treatments. It also highlights their role in culture and healing for both short term and long-lasting problems. Even with a long track record of success and strong potential in pharmacology, these medicines run into serious issues when looked at through current scientific and drug development lenses [3-4]. Many plant based formulas have trouble dissolving in water, passing through barriers, staying stable over time, delivering steady strength, and behaving predictably in the body. Active ingredients like flavonoids, terpenoids, alkaloids, and polyphenols show strong effects in lab tests [5-6]. Yet they often lose that power in living organisms because of low absorption or quick breakdown. Variations in how plants are grown, picked, and prepared create big differences in the amounts and effectiveness of key elements [7-8]. As a result, even though these remedies remain popular, they face hurdles in getting official approval or wide recognition as reliable drugs. Nanotechnology has changed the face of medical science by providing fresh ways to tackle these problems. It deals with creating, studying, and using materials at a tiny scale, from 1-100nm. At that size, materials gain special physical and chemical traits, like bigger surface areas, higher reactivity, and adjustable light or electric features, quite unlike their larger forms [9]. In health applications, known as nanomedicine, it has pushed forward drug

delivery, detection methods, imaging tools, and tissue repair [10]. Various tiny systems, including polymer-based particles, lipid bubbles, solid lipid nanoparticles, branched structures, gels, emulsions, and metal particles, can wrap up healing compounds. They shield them from breaking down, boost their ability to dissolve, and release them steadily or right to the needed spots in the body [11-12]. Combining nanotechnology with traditional medicine goes by names like nano herbal medicine, nano phytomedicine, or nano Ayurveda [13]. This method links old healing knowledge with today's tech accuracy. Researchers wrap or attach plant actives to these tiny carriers to better absorption, extend time in the bloodstream, target exact locations, and cut down unwanted effects [14-15]. Take curcumin, the famous anti inflammation compound from turmeric. When put into polymer or lipid nanoparticles, it gains much better absorption, lasts longer, and works more effectively than plain extracts [16-17]. The same holds for nano versions of quercetin, berberine, and ginsenosides, which display stronger body handling and promise in animal studies [18-19].

Some old systems, like Ayurveda, seem to have grasped ideas close to nanoscale preparations long ago. Things like Bhasma, which are therapeutic ashes from metals or minerals, turn out under modern tools such as TEM, SEM, and XRD to include particles at nanometre sizes [20]. This finding suggests that traditional practices intuitively saw the value in smaller particles for better body use and less harm. So, integrating nanotechnology today feels like a logical extension of those early ideas, not a full swap.

Nanotechnology also fits the green and sustainable side of traditional medicine via green synthesis methods. Here plant extracts full of natural chemicals serve to reduce and stabilize metal nanoparticles, say silver, gold, or zinc oxide ones [21]. This skips toxic chemicals and matches the nature focused outlook of traditional healing. The nanoparticles made this way offer various health benefits, from fighting microbes and oxidation to battling cancer and aiding wound repair [22]. Green synthesis shows how care for the environment can team up with cutting edge materials work to create ecofriendly options over standard methods.

2. Scientific Rationale for Integrating Nanotechnology with Traditional Medicine

Evidence points to a strong scientific foundation for blending nanotechnology into traditional medicine. This approach targets persistent drawbacks in herbal preparations. Poor solubility often hampers these formulations. Low bioavailability creates further issues. Instability arises

frequently, along with imprecise dosing. Systems relying on nanocarriers create opportunities to boost delivery of natural active compounds. They also improve stability and overall therapeutic value. Changes at the nanoscale alter physical and chemical properties to achieve this. A range of nanocarrier types supports these goals. Liposomes serve as one example. Polymeric nanoparticles offer another. Solid lipid nanoparticles, known as SLNs, play a role too. Nano emulsions, nanogels, micelles, and dendrimers complete the main options. Each can encapsulate or bind to key phytochemicals from plants. Such methods enhance how these compounds move through the body and exert effects [22].

2.1 Improving Solubility and Permeability

Studies identify poor water solubility as a key hurdle in traditional medicine. Many plant-based active ingredients struggle with this. Absorption across biological barriers suffers as a result. Systemic bioavailability drops [23]. Lipophilic substances like curcumin, resveratrol, berberine, and quercetin illustrate the problem. These compounds aggregate easily in water. Precipitation follows, and dissolution slows in gut fluids.

Nanocarriers address this through targeted designs. Polymeric nanoparticles prove especially useful. Nano emulsions and micellar setups help as well. They reduce particle sizes and expand surface areas. Solubility appears to rise from these adjustments. Interactions with solvent molecules increase at the nanoscale. Dissolution rates climb, consistent with the Noyes-Whitney equation. Amphiphilic properties in many carriers allow mixed solubilization. Hydrophobic and hydrophilic compounds load together [24].

Lipid nano emulsions, for one, raise curcumin's oral bioavailability more than eight times over raw extracts. Chitosan-coated nanoparticles boost flavonoid passage in the intestines. Mucoadhesive bonds with cell layers aid this process. Surface tweaks with ligands or surfactants further permeability. Barriers like the gut lining or blood-brain divide become easier to cross. Encapsulation at small scales thus provides a logical way forward. Solubility and uptake improve measurably. These fixes tackle core weaknesses in traditional approaches.

2.2 Protection of Bioactive from Degradation

Chemical instability marks another core limit in herbal setups from tradition. Bioactive elements face breakdown easily. Polyphenols, alkaloids, and terpenoids show vulnerability. Hydrolysis, oxidation, photolysis, and enzyme actions degrade them. This occurs in storage, during mixing, or post-dosing. Sources 39 and 41 outline the risks. Curcumin degrades quickly at body pH levels. Green tea catechins oxidize under light or air exposure.

Nanocarriers create shielding environments for these sensitive items. Encapsulation in hydrophobic cores or lipid layers limits harm. Reactive oxygen species find less access. Light and enzymes stay at bay too. Shelf life extends, and circulation time in the body lengthens [22]. Release can tie to local triggers as well. pH shifts, temperature changes, or enzyme presence might prompt it. Polymeric nanoparticles respond to acidity in tumors or inflamed areas. Herbal payloads deploy there selectively. Efficacy rises in those spots. Degradation elsewhere drops. This fits treatments for ongoing issues like arthritis, cancer, or infections [25]. Nanocarriers also sidestep first-pass liver metabolism. Transdermal or mucosal routes deliver straight to circulation. Potency holds stronger this way. The idea echoes Ayurveda's Anupana concept. Vehicles carry herbs to exact tissues. Modern nanocarriers mirror that ancient strategy in scientific terms.

2.3 Controlled and Targeted Drug Release

Traditional systems struggle with release timing and location. Plasma levels swing unpredictably. Outcomes vary as a result [26]. Nanotechnology counters this with structured controls. Release happens at set rates and sites. Concentrations hit targets just right for the needed time.

Carrier makeup and build dictate controlled release. Biodegradable options like PLGA or PCL break down slowly. Bioactive emerge over long stretches. Dosing needs drop. Compliance improves for patients. Effects mimic those from extended polyherbal traditions [26]. Targeting adds precision through added features. Ligands like antibodies, peptides, or sugars bind specific cell markers. Folate-linked nanoparticles with berberine gather in cancer sites. Folate receptors pull them in. Anticancer action strengthens without harming healthy tissue [13]. Mannose coatings direct anti-inflammatory herbals to macrophages. Inflammatory conditions benefit.

These methods reflect Ayurveda's Prabhava idea. Herbs act uniquely at certain sites. Nanocarriers give a measurable explanation for that selectivity. Traditional delivery gains modern backing. Core ideas find validation through science.

2.4 Enhancement of Therapeutic Index and Reduction of Toxicity

The therapeutic index measures safety by comparing toxic and effective doses. It guides clinical use closely. Herbal medicines carry risks despite natural origins. High doses or long use might harm liver, kidneys, or blood [27]. Nanocarriers widen the index via focused delivery. Systemic spread of actives lessens.

Camptothecin encapsulation in polymers cuts side effects. Anticancer power stays intact [27]. Thymoquinone from *Nigella sativa* in lipid carriers boosts anti-inflammatory results. Toxicity falls markedly in animal tests. Benefits maximize while harms minimize. This principle unites nanomedicine and traditional views.

Co-delivery of herbals in mixes enhances synergy too. Traditional remedies blend components for joint action. Nanocarriers control ratios and timing precisely. Effects amplify as intended. The Ayurvedic Yogavahi notion fits here. One element boost another. Safety and power improve in numbers. Traditional essence preserves through these advances.

2.5 Standardization and Quality Control

Standardization gaps hinder traditional medicine's wider use. Reproducibility falters often. Raw material differences matter. Origins and methods vary. Therapeutic results shift accordingly [29]. Data from 43 and 48 highlight the inconsistencies. Nanotechnology introduces clear metrics. Particle size, zeta potential, encapsulation rates, and release patterns quantify quality.

Tools like DLS, FTIR, TEM, and HPLC track structures and chemistry. Nano-herbal integrity holds under scrutiny [30].

3. Representative Nano formulations

Studies conducted over the past two decades point to the effective ways nanotechnology applies to traditional herbal compounds and other natural ones. Certain nano formulations

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that researchers have characterized in detail now serve as key models. These help explain gains in pharmacological effects, physical and chemical properties, and how well they work with living tissues through delivery at the nanoscale. Examples like the ones discussed next show clearly how nanotechnology boosts the treatment value of active ingredients from traditional sources.

3.1 Curcumin Nano formulations

Curcumin stands out as the main compound in *Curcuma longa*, which is turmeric. Investigations into it keep growing because of its wide range of effects. These include anti-inflammatory actions, antioxidant properties, antimicrobial power, cancer-fighting potential, and protection for nerves [30]. Still, real use in clinics faces hurdles. The compound dissolves very little in water, about 11 ng per mL. It metabolizes quickly too. And it does not spread well through the body. To push past these issues, experts created various nanocarrier options. Among them are nanoparticles from poly-lactic-co-glycolic acid, or PLGA. Then there are liposomes, solid-lipid nanoparticles, and micelles made from polymers.

Nanoparticles that wrap curcumin in PLGA measure between 100 and 200 nm across. They release the compound slowly over 48 to 72 hours. In animal tests after oral dosing, blood levels rise nearly ten times higher than without the carrier [31]. The wrapping shields curcumin from breaking down due to water or light. At the same time, it helps cells take it in via a process called endocytosis.

Formulations using liposomes for curcumin succeed a lot in tests for inflammation and cancer. The tiny lipid layers act like cell membranes in the body. This lets them blend easily with cells that need targeting [30]. In mouse models of colon cancer and breast cancer, the liposomal version cut down NF- κ B signals. Tumors shrank by over 60 percent. That beat the plain compound by far [32]. Micelle systems for curcumin rely on surfactants like Pluronic F127 or Tween 80 to form. Solubility jumps up to 5000 times. Chemical stability holds up at body pH levels. Pilot studies in clinics show better absorption overall. Anti-arthritis effects come at smaller doses too. All this points to strong chances for moving curcumin tech into wider use.

Taken together, these carrier types show how nanotech turns a hard-to-use plant chemical into something strong for medicine. It matches up well with man-made drugs in how effective and steady it stays.

3.2 Artemisinin-Based Nanocarriers

Artemisinin comes from *Artemisia annua* as a sesquiterpene lactone. It forms the base of malaria treatment in old Chinese practices and today's medicine. Water does not dissolve it easily. Plus, the body clears it fast. So, treatments call for big doses and mixes with other drugs. To fix that, polymeric nanoparticles and liposome systems loaded with artemisinin took shape [33]. Nanoparticles from PLGA or polycaprolactone hold artemisinin or related forms like artesunate and dihydroartemisinin. They resist breaking down from water or oxygen. Those count as main ways the compound loses strength and lasts less on shelves. Even better, carriers changed on the surface with things like transferrin, mannose, or heparin target red blood cells hit by infection. Plasmodium parasites live there [33]. The parasites grab more transferrin. That opens a path for the tagged nanoparticles to enter through receptors on cell surfaces.

Such carriers build up artemisinin right where the infection sits. They cut down side effects across the body. Dosing happens less often too. All that helps people stick to treatment in places where malaria spreads a lot. Outside of malaria, nano versions of artemisinin show effects against tumors and viruses. They make reactive oxygen species in sick cells on purpose. The way these nanoparticles work offers a strong example. Traditional active ingredients turn into exact treatments with help from nanotech methods.

3.3 Silymarin Solid-Lipid Nanoparticles

Silymarin extracts from *Silybum marianum*, or milk thistle, as a mix of flavonolignans. It protects the liver and appears in Ayurvedic uses along with European herb traditions. But treatment faces limits from low fat solubility and weak uptake in the gut. Solid-lipid nanoparticles, or SLNs, and nanostructured lipid carriers, or NLCs, step in as friendly delivery tools. They fit well with body processes [34]. SLNs for silymarin use natural fats like glyceryl monostearate or stearic acid. Phospholipids and surfactants keep them stable. Sizes average 80 to 120 nm. They trap over 90 percent of the compound inside. Release

stretches over 24 hours in a steady way. Studies on how the body handles drugs show oral SLNs boost availability three to five times over plain silymarin [34].

On the biology side, these nanoparticles ramp up defenses against oxidation in liver areas. Levels of glutathione and superoxide dismutase go up. Lipid damage drops too. In rats with liver harm from CCl₄, tissue exams under microscopes proved better protection. The nanoparticle form outdid raw extracts or pills sold in stores.

The lipid setup in solids breaks down naturally in the body. It scales up for making larger amounts. And it guards sensitive compounds through the gut journey. So SLNs work as flexible carriers for various liver-saving plant chemicals from traditions. The results make clear how nanotech takes an old natural fix and shapes it into something steady and ready for clinics.

3.4 Green-Synthesized Metallic Nanoparticles

A strong link between nanotech and old medicine shows up in making metallic nanoparticles the green way. Plant extracts do double duty as reducers and stabilizers. This fits the earth-friendly and whole-body views in traditional medicine. It skips toxic chemicals and energy-heavy steps [35]. Plant chemicals like phenolics, terpenoids, alkaloids, and flavonoids cut metal ions such as Ag⁺, Au³⁺, or Zn²⁺ down to nanoparticle form. They also coat and steady the tiny structures. Extracts from *Azadirachta indica*, or neem, *Ocimum sanctum*, known as holy basil, and *Moringa oleifera* get used a lot. They produce silver nanoparticles, or AgNPs, and gold ones, or AuNPs. Sizes stay between 10 and 50 nm. Shapes come out controlled [35]. These particles made green show strong effects against microbes across types, oxidation, and cancer growth. Silver ones from neem leaves stop Gram-positive and Gram-negative bacteria. They break up biofilms too. And they team up well with standard antibiotics. Gold nanoparticles from holy basil kill off MCF-7 breast cancer cells and HeLa cervical ones in a targeted way. They work through making reactive oxygen species and messing with mitochondria.

Past health uses, this green making blends old plant know-how with new nano chemistry. It stands for ongoing changes that last. Researchers keep checking how repeatable the methods are. They also test fit with official drug standards.

3.5 Ayurvedic Bhasmas. Natural Nanomedicines

Ayurvedic Bhasmas offer a special case of tiny scale materials in old medicine. These calcined metals or minerals have treated people in India for hundreds of years. Examples include Swarna Bhasma from gold, Abhraka Bhasma from mica, and Tamra Bhasma from copper. The process repeats purification, called Shodhana, and heating, or Marana, with plant juices or brews. This ends up creating particles at nano sizes by chance.

Tools like Transmission Electron Microscopy, or TEM, Scanning Electron Microscopy, or SEM, X-ray Diffraction, or XRD, and Energy-Dispersive X-ray Analysis, or EDX, now prove sizes from 50 to 80 nm in gold and mica Bhasmas [36]. Often the particles sit inside organic layers from the herbs in heating. That boosts how well they fit the body and spread.

In terms of drug effects, gold Bhasma aids immune balance, fights joint swelling, and guards nerves. Mica Bhasma handles oxidation and builds blood. The small size lets cells take them in easily. That might explain why old texts note high strength at low amounts. Plus, the careful metal work in making Bhasmas hints at early grasp of nano ideas, way before the term existed.

Research today focuses on standard ways to make Bhasmas. It checks safety with lab and animal tests that fit modern views. Such work confirms the trial-and-error smarts in Ayurveda. It also sets Bhasmas as early natural forms of metal-based nano drugs.

4. Safety and Regulatory Aspects

Nanocarriers have transformed the way traditional medicines perform in therapy. At the same time, they create specific toxicological and regulatory hurdles. Nanoscale formulations differ from standard herbal extracts. They engage with biological systems right at the molecular and cellular scales. Without careful design and testing, this engagement might trigger oxidative stress, genotoxicity, or buildup in organs [37]. Those same traits that boost nanoparticle effectiveness, high surface area along with reactivity and permeability, often lead to unwanted effects too. Non-specific contacts happen with cell membranes, mitochondria, and even DNA. All of this points to safety issues that demand thorough, step-by-step handling.

4.1 Toxicological Concerns

Research has shown how certain inorganic nanoparticles, things like silver, zinc oxide, or titanium dioxide, spark reactive oxygen species production. That leads to lipid peroxidation, inflammation, and cell death through apoptosis in mammalian cells [37]. Over time, repeated exposure or buildup of non-breakdown materials in places like the liver, spleen, and kidneys could bring lasting harm. Toxicity checks cannot stick just to old measures such as LD50 values or blood counts. Instead, they need specialized tests for nanoparticles. Think oxidative stress indicators, profiles of cytokines, and images of how they spread in the body.

4.2 Regulatory Framework

Agencies like the U.S. Food and Drug Administration, the European Medicines Agency, and the Organization for Economic Co-operation and Development see these issues. They put out guidelines that call for risk reviews tailored to each nanomedicine case [38]. No one-size-fits-all rules apply here. Makers have to supply in-depth info on nanoparticle details. That covers size, surface charge, shape, and how stable they stay. Plus, toxicokinetics and how they break down over time.

When it comes to nano formulations built from traditional medicine, extra caution makes sense. Herbal extracts carry built-in complexity with various active parts. Those parts might react in unique ways with the carriers. The FDA labels these nano-herbal items as complex drug substances right now. So, they face standards from both botany and nanotechnology sides. The EMA pushes for adding nano-focused safety files during product approval. That helps meet rules on watching for side effects after launch.

4.3 Safe-by-Design Approaches

Safe-by-Design stands out as a forward-thinking way to build nanomedicines. It focuses on picking materials that work well with biology and break down safely. Examples include PLGA, chitosan, alginate, and gelatin. These cut down on harm risks while still delivering drugs effectively [39]. Take PLGA nanoparticles for instance. They turn into lactic and glycolic acids through breakdown. The body handles those naturally in the Krebs cycle. Long-term toxicity ends up almost none at all. Chitosan comes from shellfish shells. It sticks to mucus, fights microbes, and stays non-toxic plus fully biodegradable.

Lately, metallic nanoparticles made through green methods show up as better options than those from chemicals. Plant extracts handle the synthesis with phytochemicals acting as reducers. This skips dangerous agents and lowers risks to the environment and biology [39].
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On top of that, wrapping metallic particles in biopolymers or sugars adjusts their surface charge. It boosts how well they work with blood too.

4.4 Global Safety Initiatives

The World Health Organizations Global Centre for Traditional Medicine opened in India back in 2022. It highlights the push for standard ways to check safety in nano-herbal setups [40]. Efforts aim to align testing before clinical use, validation in trials, and monitoring after products hit the market. All this for nano versions of traditional medicines around the world. The WHO plan pushes teamwork among regulators, traditional healers, and nanotech experts. The goal stays clear. Boosting effectiveness should never undercut safety.

Wrapping up here, striking a balance between new ideas and caution matters a lot. Bringing nanotechnology into traditional medicine calls for sticking to shared global rules on toxicology, the environment, and ethics. That builds trust, makes results repeatable, and protects patients in the end.

5. Socio-Ethical and Economic Considerations

Nanotechnology mixed with traditional medicine goes further than lab work alone. It reaches into ethics, society, and money matters too. Those shape how people accept it and share benefits fairly.

5.1 Respecting Traditional Knowledge Systems

Systems like Ayurveda, Traditional Chinese Medicine, and African ethnomedicine hold ages of hands-on knowledge and cultural roots. Turning them into high-tech forms brings up questions on who owns that wisdom and how to protect intellectual property. The Nagoya Protocol from 2014 sets rules on this. Any use of biological resources or local knowledge for business or study requires fair pay and credit to the communities involved [41]. So, researchers working on nano versions from local plants follow local laws on biodiversity and property rights. They keep partnerships open and spread benefits evenly.

5.2 Economic Sustainability and Local Empowerment

One big plus in blending nanotechnology with traditional medicine comes from making production cheap and based on local stuff. Green synthesis relies on plant extracts, biopolymers, or farm leftovers. That cuts need for costly chemicals and big setups. It fits with sustainable development goals by creating jobs in rural areas, saving biodiversity, and

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building circular economies [35]. Small and medium businesses in poorer countries step up here. They make nano-herbal pills or skin products from home resources. This boosts local money flows and lessens reliance on imported fake drugs.

5.3 Public Awareness and Ethical Transparency

Even with these upsides, doubt from the public slows down uptake of updated traditional formulas. Fears about tampering with old remedies often come from wrong info or just not knowing better. So, governments and schools run programs, talks, and classes to clear things up. Nanotechnology helps keep and improve traditional medicine, not swap it out [43]. On the ethics side, being open counts. Labels that explain clearly, details on nano parts, and talks about safety tests all help. That grows confidence and eases rule-following.

6. Current Trends

6.1 Publication and Research Growth

Counts from bibliometrics show publications on nano-herbal medicine shooting up fast from 2010 to 2025. The yearly growth rate tops 15% in worldwide output [44]. Most work comes out of India, China, and Iran. Those places have deep roots in traditional medicine and growing nanotech setups.

6.2 Focused Research Areas

Hot areas now cover nano-curcumin, nano-resveratrol, and metal nanoparticles from green synthesis. They target cancer, infections from microbes, diabetes, and healing wounds [45]. Work stresses platforms that do multiple jobs at once. One setup might handle antioxidants, microbe fighting, and cutting inflammation all together. Hybrid setups push this further. Magnetic-liposomal mixes or metal particles coated in polymers add more ways to treat.

6.3 Digital Integration and Artificial Intelligence

A fresh area grows quick with Artificial Intelligence and Machine Learning tied into designing and tweaking nano-herbal formulas. AI tools guess how nanoparticles link with biomolecules. They fine-tune steps in making them and model how drugs move in the body through computer sims [46]. This speeds up creating formulas, trims costs on experiments, and backs precision medicine. Formulas get customized to what patients need exactly. Using AI for design marks the move to smart, data-based updates in traditional medicine.

7. Challenges and Future Directions

Progress looks strong, yet scientific and rule-based roadblocks linger. They block nano-traditional medicines from wide clinical use.

7.1 Key Limitations

Clinical Evidence Stays Limited

In vitro and animal work backs up better results from nano traditional medicines. But big, random trials with humans stay few and far between [47]. Solid human proof lacks, so claims on therapy and dose standards prove hard to set.

Long-Term Toxicity and Environmental Impact Need

Lots of studies skip chronic effects and how nanoparticles break down, especially metals [48]. Figuring out buildup over time, removal from body, and eco harm stays key for lasting use.

Multi-Component Systems Bring Complexity

Traditional mixes hold many phytochemicals acting up differently with carriers. That muddies checking them, repeating results. Better tools like LC-MS/MS, Raman spectroscopy, and tracking nanoparticle movement help untangle it all.

Regulatory Fragmentation Creates Hurdles

No shared global rules for nano-traditional items lead to confusion. That slows sales and trade across borders. Unified setups could smooth approvals.

7.2 Strategic Recommendations for Future Research

Future efforts to blend nanotechnology and traditional medicine fully should focus on a few main steps. Large-scale clinical trials come first. They set safety, effectiveness, and drug movement. Eco-friendly green synthesis paths follow. Those cut waste and energy use. Standard checks and quality controls for nano-herbal items ensure steady batches. Digital aids like AI and ML optimize settings, guess toxicity, and speed early tests. Global policy setups through WHO, FDA, and local groups tie traditional validation with nanoscience rules into one system.

8. Conclusion

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The integration of nanotechnology with traditional medicine provides a scientifically grounded pathway to modernize ancient healing systems. By merging biocultural wisdom with nanoscale precision, it becomes possible to enhance bioavailability, therapeutic efficacy, and safety of herbal drugs. Continued interdisciplinary collaboration, ethical governance, and standardized regulations will determine the success of nano-traditional medicine as a sustainable healthcare paradigm.

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